Editors' Suggestion

Combination of the Searches for Pair-Produced Vectorlike Partners of the Third-Generation Quarks at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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A combination of the searches for pair-produced vectorlike partners of the top and bottom quarks in various decay channels ($T \to Zt/Wb/Ht$, $B \to Zb/Wt/Hb$) is performed using 36.1 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider. The observed data are found to be in good agreement with the standard model background prediction in all individual searches. Therefore, combined 95% confidence-level upper limits are set on the production cross section for a range of vectorlike quark scenarios, significantly improving upon the reach of the individual searches. Model-independent limits are set assuming the vectorlike quarks decay to standard model particles. A singlet T is excluded for masses below 1.31 TeV and a singlet B is excluded for masses below 1.22 TeV. Assuming a weak isospin (T, B) doublet and $|V_{Tb}| \ll |V_{tB}|$, T and B masses below 1.37 TeV are excluded.

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Introduction.—Naturalness arguments [1] suggest there should be a mechanism that cancels out the quadratically divergent contributions to the Higgs boson mass caused by radiative corrections from standard model (SM) particles. Several explanations are proposed in theories beyond the SM. Little Higgs [2,3] and composite Higgs [4,5] models introduce a spontaneously broken global symmetry, with the Higgs boson emerging as a pseudo Nambu-Goldstone boson [6]. Such models predict the existence of vectorlike quarks (VLQs), color-triplet spin-1/2 fermions whose left- and right-handed chiralities transform in the same way under weak isospin [7,8]. In these models, VLQs are expected to couple preferentially to third-generation quarks [7,9] and can have flavor-changing neutral-current decays in addition to charged-current decays. An up-type VLQ T with charge $+2/3$ can decay into Wb, Zt, or Ht. Similarly, a down-type quark B with charge $-1/3$ can decay into Wt, Zb, or Hb. In order to be consistent with results from precision electroweak measurements, the mass-splitting between VLQs belonging to the same SU(2) multiplet is required to be small [10], forbidding cascade decays such as $T \to WB$. Couplings between the VLQs and the first- and second-generation quarks, although not favored, are not excluded [11,12].

At the Large Hadron Collider (LHC), VLQs with masses below approximately 1 TeV would mainly be pair produced, a process dominated by the strong interaction. The corresponding predicted cross section ranges from 195 to 2.0 fb for quark masses from 800 to 1500 GeV [13] and depends only on the quark mass. Production of single VLQs via the electroweak interaction is also possible, but depends on the strength of the interaction between the new quarks and the weak gauge bosons. Representative Feynman diagrams for $B\bar{B}$ and $T\bar{T}$ production and decay are shown in Fig. 1.

The branching ratio ($\mathcal{B}$) for each decay mode ($T \to Wb, Zt, Ht$ and $B \to Wt, Zb, Hb$) depends on the VLQ mass and weak-isospin quantum numbers, as calculated in Ref. [8]. For a singlet T, all three decay modes have sizable branching ratios, while the charged-current decay mode $T \to Wb$ is absent if T is either in a (X, T) doublet, where X is a VLQ with a charge of $+5/3$, or in a (T, B) doublet with $|V_{Tb}| \ll |V_{tB}|$, where V_{ij} are the elements of a generalized Cabibbo-Kobayashi-Maskawa matrix [8,14,15]. Since the T quark branching ratios are identical in both doublets, no distinction is made between them when referring to the doublet T results. A singlet B will have a sizable branching ratio to all three decay channels, while the branching ratios in the doublet case depend on whether it is in a (T, B) doublet or (B, Y) doublet, where Y is a VLQ with a charge of $-4/3$. For a (B, Y) doublet, only neutral current couplings to SM quarks are allowed at leading order (LO), so the $B \to Wt$ decay is forbidden. Conversely, for a (T, B) doublet with $|V_{Tb}| \ll |V_{tB}|$, $B \to Wt$ is the only allowed decay. Therefore, the specific B doublet scenario will be stated when interpreting the results.

Contributing analyses.—Searches for pair-produced VLQ partners of the third-generation quarks have been performed by ATLAS [16–22] and CMS [23–25] at the

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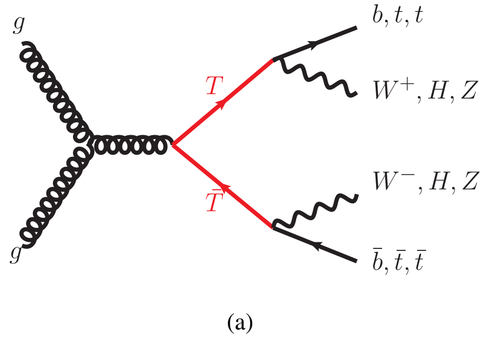

FIG. 1. Representative leading-order Feynman diagrams for (a) $T\bar{T}$ and (b) $B\bar{B}$ pair production. The studied VLQ decays are also displayed.

LHC at $\sqrt{s} = 13$ TeV. This Letter presents the full combination of the ATLAS searches using 36.1 fb^{-1} of data collected in 2015 and 2016. The ATLAS detector is described in Ref. [26]. Below is a brief description of each contributing analysis.

$H(bb)t + X$ [16]: The primary targets of this analysis are $T\bar{T}$ events with at least one VLQ decaying into Ht, with $H \to b\bar{b}$. Events must have at least six jets [27] and either one lepton (electron [28] or muon [29]) or missing transverse momentum [30] $E_T^{miss} > 200$ GeV with zero leptons. The analysis uses b-tagging [31,32] as well as dedicated top and Higgs jet tagging to classify the events into 22 and 12 search regions for the zero-lepton and one-lepton selections, respectively. The final discriminant is the scalar sum (S_T) of the transverse momenta of the selected jets, lepton, and missing transverse momentum. The dominant background is the associated production of a $t\bar{t}$ pair with b- and c-quark jets, which is modeled via Monte Carlo (MC) simulation and assigned dedicated modeling uncertainties.

$W(\ell\nu)b + X$ [17]: This analysis primarily targets $T\bar{T} \to WbWb$ events with one W decaying leptonically and the other hadronically. Event selection requires one lepton, ≥ 3 jets, at least one of them being b-tagged, and a hadronically decaying W boson identified using jet substructure techniques [33]. The final discriminant is the reconstructed mass of the $T \to Wb \to \ell\nu b$ candidate. The dominant background is from $t\bar{t}$ pair production, which is modeled using MC simulation with dedicated modeling uncertainties.

$W(\ell\nu)t + X$ [18]: Very similar to the $W(\ell\nu)b + X$ analysis, this analysis is optimized to target $B\bar{B}$ signals, especially in the case where $B \to Wt$. This analysis discriminates between the signal and the dominant $t\bar{t}$ background in the signal regions using either a boosted decision tree discriminant or the reconstructed mass of the B candidate.

$Z(\nu\nu)t + X$ [19]: This analysis targets $T\bar{T} \to ZtZt$ events with an invisible Z decay. Events must have $E_T^{miss} > 300$ GeV, one charged lepton from the decay of a top quark, and ≥ 4 small-radius jets, which are reclustered [34] into large-radius jets. The analysis defines a single-bin signal region that capitalizes on various E_T^{miss}-based variables and requires at least two high-mass large-radius jets due to hadronically decaying top quarks and/or heavy bosons from the VLQ decays. The dominant backgrounds are $t\bar{t}$ + jets, W + jets, and single-top events, which are estimated from MC simulation and normalized using dedicated control regions.

$Z(\ell\ell)t/b + X$ [20]: This analysis searches for $T\bar{T}$ and $B\bar{B}$ events containing a leptonically decaying Z boson ($Z \to \ell^+\ell^-$) and at least two b-jets. The analysis has one trilepton signal region and three dilepton signal regions, depending on the number of large-radius jets (0, 1, or ≥ 2). The final discriminant depends on the signal region. The dominant backgrounds for the dilepton channels are Z + jets and/or $t\bar{t}$ and diboson, while the trilepton channels are dominated by diboson (WZ) and $t\bar{t}Z$ events, each modeled by MC simulation and validated with dedicated control regions.

Trilepton or same-sign dilepton [21]: This analysis targets $T\bar{T}$ and $B\bar{B}$ decays with multilepton final states, with particular emphasis on events containing a pair of charged leptons with the same electric charge ("same sign"). Eight single-bin signal regions are defined in accord with the number of leptons and b-tagged jets. The background composition for this analysis varies between signal regions. Contributions from instrumental backgrounds (fake or nonprompt leptons and electrons with incorrectly measured charge) are estimated using data-driven techniques, while background processes with prompt leptons, originating mostly from $t\bar{t} + W$ and diboson events, are modeled with MC simulations.

Fully hadronic [22]: This analysis focuses on final states with zero leptons, low E_T^{miss}, at least four (small-radius) high-p_T jets, and at least two b-tagged jets. This is the only analysis with significant sensitivity to $B\bar{B} \to HbH\bar{b}$. Small-radius jets are reclustered into large-radius jets, which may be identified as top quarks, W/Z, or H bosons using a multiclass deep neural network [35]. The final discriminant is the distribution of the signal likelihood calculated using the matrix-element method [36]. The dominant background is from multijet production, which is estimated using a data-driven technique.

TABLE I. The most sensitive decay channel for each analysis entering the combination. A "$\cdots$" indicates that the analysis was not used for that signal process.

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	$\cdots$
$W(\ell\nu)b + X$ [17]	$WbW\bar{b}$	$\cdots$
$W(\ell\nu)t + X$ [18]	$\cdots$	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [19]	$ZtZ\bar{t}$	$\cdots$
$Z(\ell\ell)t/b + X$ [20]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [21]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [22]	$HtH\bar{t}$	$HbH\bar{b}$

Most of the analyses were designed to be complementary. While each analysis provides sensitivity to various decay configurations, the most sensitive is shown in Table I. All analyses use consistent definitions for the reconstructed physics objects, so only a few additional selection requirements were needed to suppress overlap. Compared to the standalone analyses, the $W(\ell\nu)b + X$ and $Z(\nu\nu)t + X$ analyses removed events with ≥ 6 jets and ≥ 3 b-jets to avoid overlap with the $H(bb)t + X$ selection. The $Z(\nu\nu)t + X$ analysis also requires $S_T < 1.8$ TeV in a control region to mitigate the overlap with a signal region in the $W(\ell\nu)b + X$ analysis. To reduce overlap with the $Z(\ell\ell)t/b + X$ analysis, the trilepton or same-sign dilepton analysis removed events with more than three leptons or events with a lepton pair having an invariant mass compatible with a Z boson (Z veto). This Z veto is the only added selection requirement with significant impact on the individual analysis sensitivity; however, that sensitivity is recovered by the $Z(\ell\ell)t/b + X$ analysis. After applying these additional selection requirements, the fraction of events falling into more than one analysis region was evaluated to be less than 1% between any two signal regions and less than 3% between any pair of signal or control regions and has negligible impact on the results.

The VLQ signal samples used by the analyses were generated with the LO generator PROTOS v2.2 [37] using the NNPDF2.3 LO [38] set of parton distribution functions (PDF) and passed to PYTHIA 8.186 [39] for parton showering and fragmentation. The samples are normalized using cross sections computed with TOP++ v2.0 [13] at next-to-next-to-leading order (NNLO) in QCD, including resummation of next-to-next-to-leading logarithmic soft gluon terms [40–44], and using the MSTW 2008 NNLO [45,46] PDF. Further information about simulated events and details of the background estimations for each analysis can be found in the respective publications.

Statistical analysis.—The statistical analysis is the same as in the individual analyses and is based on a binned likelihood function constructed as the product of the Poisson probabilities of all bins entering the combination. This function depends on the signal-strength parameter μ, a factor multiplying the theoretical signal cross section ($\mu \equiv \sigma/\sigma_{\text{theory}}$), and a set of nuisance parameters that encode the effect of the systematic uncertainties on the signal and background expectations. These parameters are included with Gaussian or log-normal constraints. Additional unconstrained nuisance parameters are included to control the normalization of the main backgrounds, following the settings used in the standalone searches. The combination is achieved by performing a fit with all bins from all the regions considered from each analysis.

The analysis is limited by statistical uncertainties, and the precise correlation model for the systematic

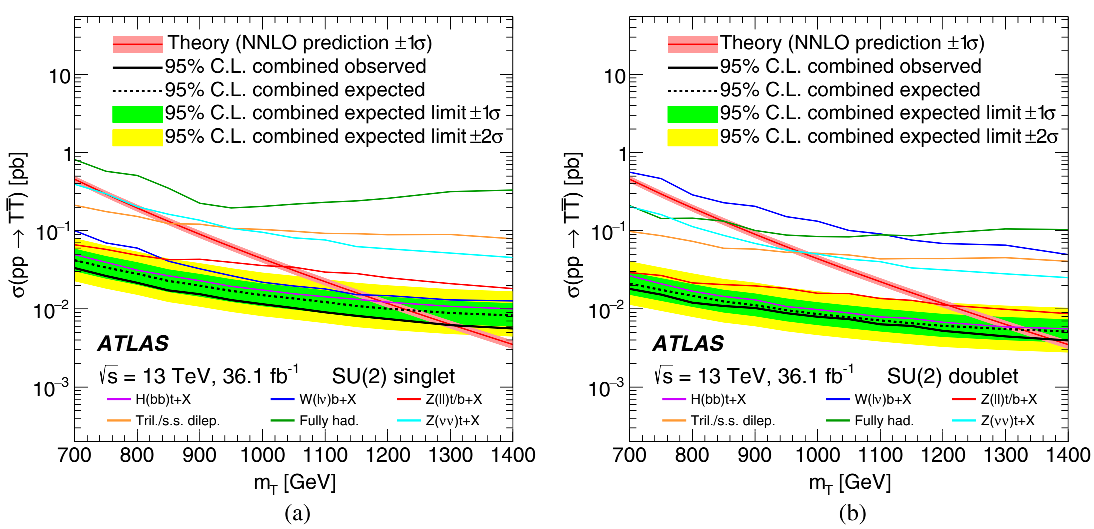

FIG. 2. Observed (solid lines) and expected (dashed line) 95% C.L. upper limits on the $T\bar{T}$ cross section versus mass for the combination and the standalone analyses in black and colored lines, respectively. The (a) singlet and (b) doublet scenarios [8] are displayed. The shaded bands correspond to ± 1 and ± 2 standard deviations around the combined expected limit. The rapidly falling thin red line and band show the theory prediction and corresponding uncertainty [13], respectively.

uncertainties was found to not significantly affect the results. The detector-related uncertainties are treated as fully correlated across analyses, with the following exceptions. The central values and uncertainties of the b-tagging and the luminosity measurement were updated after the publication of the $Z(\nu\nu)t+X$ and $W(\ell\nu)b+X$ analyses. Therefore, to avoid propagating constraints caused by the change in the method, these uncertainties are correlated between the $Z(\nu\nu)t+X$ and $W(\ell\nu)b+X$ analyses, but uncorrelated with the other searches, which are correlated among themselves. The modeling uncertainties and background normalization parameters are treated as uncorrelated between analyses. Although some background processes are common to multiple analyses, the phase space and the techniques used to estimate those backgrounds can be quite different. Residual correlations are therefore expected to be negligible.

Results.—The behavior of the combination is consistent with the fits from the individual analyses. The postfit values of all nuisance parameters are compatible with the standalone analyses, with the constraints generally determined by the analysis most sensitive to the given nuisance parameter. Similarly, the background predictions in each analysis after the combined fit are very close to the results from the standalone analyses. After the combination, no significant excess is observed in the data, so 95% confidence level (C.L.) limits are set on the cross section of a VLQ signal. To increase the applicability and usefulness of this combination, limits are evaluated both for benchmark scenarios with specific

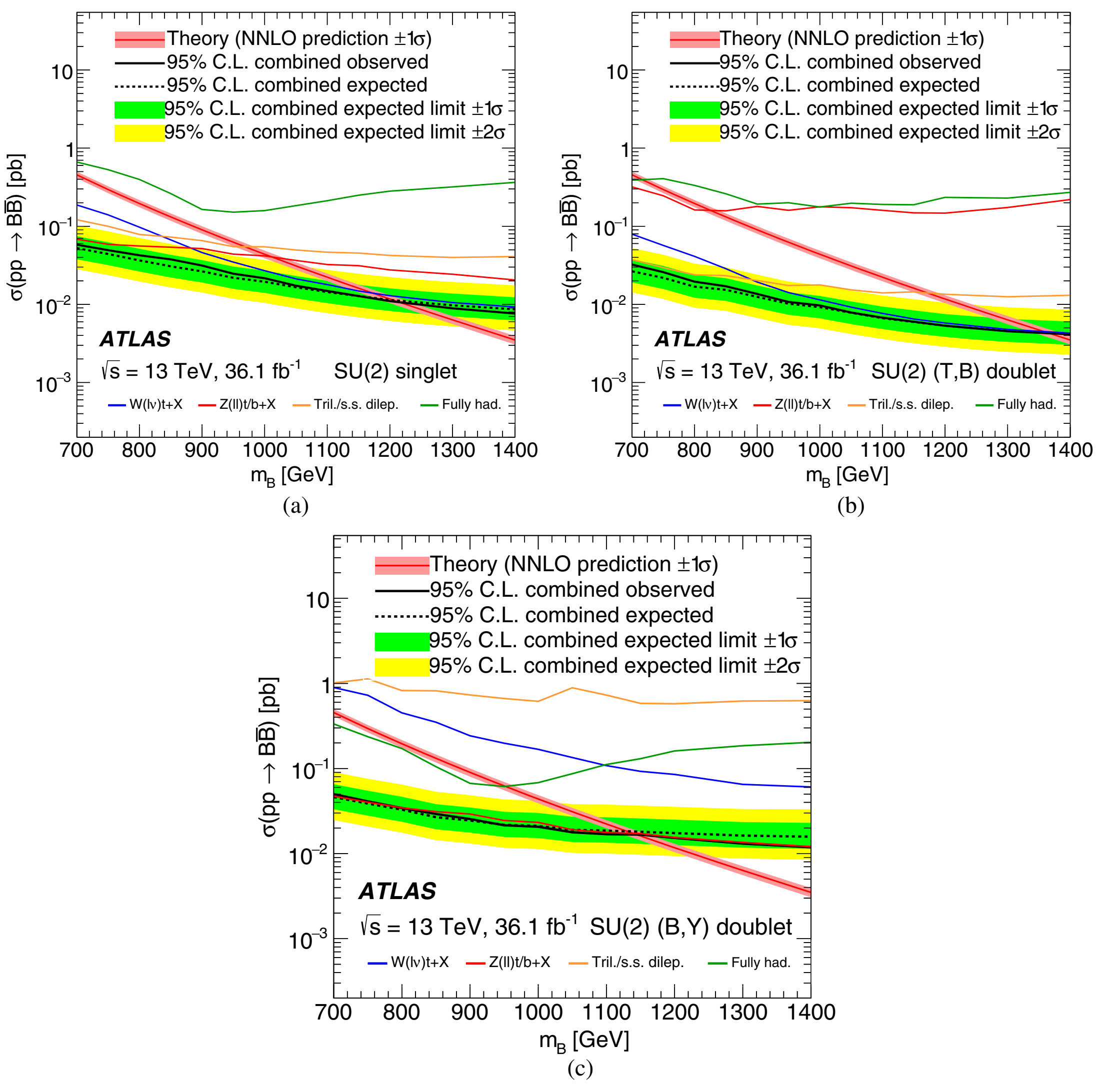

FIG. 3. Observed (solid lines) and expected (dashed line) 95% C.L. upper limits on the $B\bar{B}$ cross section versus mass for the combination and the standalone analyses in black and colored lines, respectively. The (a) singlet, (b) (T,B) doublet, and (c) (B,Y) doublet scenarios [8] are displayed. The shaded bands correspond to ±1 and ±2 standard deviations around the combined expected limit. The rapidly falling thin red line and band show the theory prediction and corresponding uncertainty [13], respectively.

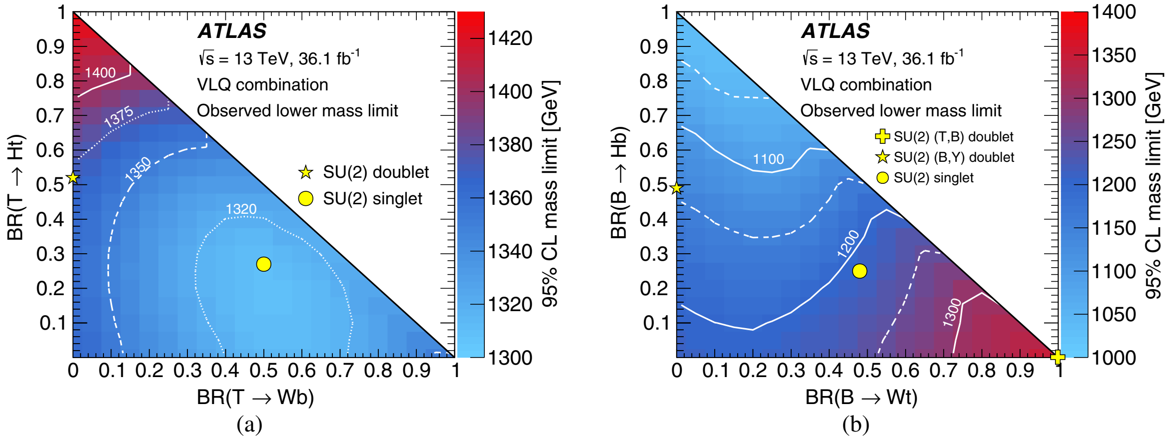

FIG. 4. Observed lower limits at 95% C.L. on the mass of the (a) T and (b) B as a function of branching ratio assuming $\mathcal{B}(T \to Ht) + \mathcal{B}(T \to Zt) + \mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B \to Hb) + \mathcal{B}(B \to Zb) + \mathcal{B}(B \to Wt) = 1$. The yellow markers indicate the branching ratios for the SU(2) singlet and doublet scenarios where the branching ratios become approximately independent of the VLQ mass [8].

branching ratios and for general combinations of branching ratios.

For an assumed set of branching ratios, upper limits are set on the production cross sections for $T\bar{T}$ and $B\bar{B}$ as a function of the VLQ mass using the $\mathrm{CL_s}$ method [47,48] with the asymptotic approximation [49]. Observed and expected upper limits on the $T\bar{T}$ cross sections as a function of mass are shown in Fig. 2 for the benchmark scenarios of an isospin singlet or doublet T. Analogous limits on the $B\bar{B}$ cross section are shown in Fig. 3. The observed limits from the individual analyses, after the additional selections defined in this Letter, are also shown. For a singlet T, masses below 1.31 TeV are excluded, while a T in an isospin doublet is excluded for masses below 1.37 TeV. A singlet B is excluded for masses below 1.22 TeV, a B in a (T, B) doublet is excluded for masses below 1.37 TeV, and a B in a (B, Y) doublet is excluded for masses below 1.14 TeV.

The combination is significantly more sensitive than any one analysis. For example, in the case of the SU(2) singlet, the observed limit on the $T\bar{T}$ cross section is improved by up to a factor of $\sim$1.7, which translates to an increase of 110 GeV in the observed mass limit.

In addition, model-independent lower limits are set on the VLQ mass for all combinations of branching ratios, assuming $\mathcal{B}(T \to Ht) + \mathcal{B}(T \to Zt) + \mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B \to Hb) + \mathcal{B}(B \to Zb) + \mathcal{B}(B \to Wt) = 1$. The resulting lower limits on the VLQ mass as a function of branching ratio are presented in Fig. 4. Limits corresponding to $\mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B \to Wt) = 1$ are found to also be applicable to $Y\bar{Y} \to WbWb$ and $X\bar{X} \to WtWt$, respectively. The high degree of complementarity between the analyses is clearly demonstrated in Fig. 4. For *any* combination of branching ratios, the combined analysis leads to observed (expected) lower mass limits of 1.31 (1.22) TeV for T and 1.03 (0.98) TeV for B. Limits on the signal strength, which can be used to interpret the results in scenarios with additional VLQ decays that escape detection [50], are available in the HEPData repository [51,52].

Conclusion.—The ATLAS Collaboration has performed a combination of seven analyses searching for pair-produced VLQs. Upper limits on the cross section are determined and used to set lower limits on the VLQ mass for various benchmark scenarios and for general combinations of branching ratios. This combination results in the most stringent limits to date on VLQ pair production. Because of the high degree of complementarity between the analyses, the combination has significantly better sensitivity than the standalone analyses, for the first time excluding T (B) masses below 1.31 (1.03) TeV for *any* combination of decays into SM particles.

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M. Aaboud,[34d] G. Aad,[99] B. Abbott,[124] O. Abdinov,[13,a] B. Abeloos,[128] D. K. Abhayasinghe,[91] S. H. Abidi,[164] O. S. AbouZeid,[39] N. L. Abraham,[153] H. Abramowicz,[158] H. Abreu,[157] Y. Abulaiti,[6] B. S. Acharya,[64a,64b,b] S. Adachi,[160] L. Adam,[97] L. Adamczyk,[81a] J. Adelman,[119] M. Adersberger,[112] A. Adiguzel,[12c,c] T. Adye,[141] A. A. Affolder,[143] Y. Afik,[157] C. Agheorghiesei,[27c] J. A. Aguilar-Saavedra,[136f,136a] F. Ahmadov,[77,d] G. Aielli,[71a,71b] S. Akatsuka,[83] T. P. A. Åkesson,[94] E. Akilli,[52] A. V. Akimov,[108] G. L. Alberghi,[23b,23a] J. Albert,[173] P. Albicocco,[49] M. J. Alconada Verzini,[86] S. Alderweireldt,[117] M. Aleksa,[35] I. N. Aleksandrov,[77] C. Alexa,[27b] T. Alexopoulos,[10] M. Alhroob,[124] B. Ali,[138] G. Alimonti,[66a] J. Alison,[36] S. P. Alkire,[145] C. Allaire,[128] B. M. M. Allbrooke,[153] B. W. Allen,[127] P. P. Allport,[21] A. Aloisio,[67a,67b] A. Alonso,[39] F. Alonso,[86] C. Alpigiani,[145] A. A. Alshehri,[55] M. I. Alstaty,[99] B. Alvarez Gonzalez,[35] D. Álvarez Piqueras,[171] M. G. Alviggi,[67a,67b] B. T. Amadio,[18] Y. Amaral Coutinho,[78b] A. Ambler,[101] L. Ambroz,[131] C. Amelung,[26] D. Amidei,[103] S. P. Amor Dos Santos,[136a,136c] S. Amoroso,[44] C. S. Amrouche,[52] C. Anastopoulos,[146] L. S. Ancu,[52] N. Andari,[142] T. Andeen,[11] C. F. Anders,[59b] J. K. Anders,[20] K. J. Anderson,[36] A. Andreazza,[66a,66b] V. Andrei,[59a] C. R. Anelli,[173] S. Angelidakis,[37] I. Angelozzi,[118] A. Angerami,[38] A. V. Anisenkov,[120b,120a] A. Annovi,[69a] C. Antel,[59a] M. T. Anthony,[146] M. Antonelli,[49] D. J. A. Antrim,[168] F. Anulli,[70a] M. Aoki,[79] J. A. Aparisi Pozo,[171] L. Aperio Bella,[35] G. Arabidze,[104] J. P. Araque,[136a] V. Araujo Ferraz,[78b] R. Araujo Pereira,[78b] A. T. H. Arce,[47] R. E. Ardell,[91] F. A. Arduh,[86] J-F. Arguin,[107] S. Argyropoulos,[75] A. J. Armbruster,[35] L. J. Armitage,[90] A. Armstrong,[168] O. Arnaez,[164] H. Arnold,[118] M. Arratia,[31] O. Arslan,[24] A. Artamonov,[109,a] G. Artoni,[131] S. Artz,[97] S. Asai,[160] N. Asbah,[57] E. M. Asimakopoulou,[169] L. Asquith,[153] K. Assamagan,[29] R. Astalos,[28a] R. J. Atkin,[32a] M. Atkinson,[170] N. B. Atlay,[148] K. Augsten,[138] G. Avolio,[35] R. Avramidou,[58a] M. K. Ayoub,[15a] A. M. Azoulay,[165b] G. Azuelos,[107,e] A. E. Baas,[59a] M. J. Baca,[21] H. Bachacou,[142] K. Bachas,[65a,65b] M. Backes,[131] P. Bagnaia,[70a,70b] M. Bahmani,[82] H. Bahrasemani,[149] A. J. Bailey,[171] J. T. Baines,[141] M. Bajic,[39] C. Bakalis,[10] O. K. Baker,[180] P. J. Bakker,[118] D. Bakshi Gupta,[8] S. Balaji,[154] E. M. Baldin,[120b,120a] P. Balek,[177] F. Balli,[142] W. K. Balunas,[133] J. Balz,[97] E. Banas,[82] A. Bandyopadhyay,[24] S. Banerjee,[178,f] A. A. E. Bannoura,[179] L. Barak,[158] W. M. Barbe,[37] E. L. Barberio,[102] D. Barberis,[53b,53a] M. Barbero,[99] T. Barillari,[113] M-S. Barisits,[35] J. Barkeloo,[127] T. Barklow,[150] R. Barnea,[157] S. L. Barnes,[58c] B. M. Barnett,[141] R. M. Barnett,[18] Z. Barnovska-Blenessy,[58a] A. Baroncelli,[72a] G. Barone,[29] A. J. Barr,[131] L. Barranco Navarro,[171] F. Barreiro,[96] J. Barreiro Guimarães da Costa,[15a] R. Bartoldus,[150] A. E. Barton,[87] P. Bartos,[28a] A. Basalaev,[134] A. Bassalat,[128] R. L. Bates,[55] S. J. Batista,[164] S. Batlamous,[34e] J. R. Batley,[31] M. Battaglia,[143] M. Bauce,[70a,70b] F. Bauer,[142] K. T. Bauer,[168] H. S. Bawa,[150,g] J. B. Beacham,[122] T. Beau,[132] P. H. Beauchemin,[167] P. Bechtle,[24] H. C. Beck,[51] H. P. Beck,[20,h] K. Becker,[50] M. Becker,[97] C. Becot,[44] A. Beddall,[12d] A. J. Beddall,[12a] V. A. Bednyakov,[77] M. Bedognetti,[118] C. P. Bee,[152] T. A. Beermann,[74] M. Begalli,[78b] M. Begel,[29] A. Behera,[152] J. K. Behr,[44] A. S. Bell,[92] G. Bella,[158] L. Bellagamba,[23b] A. Bellerive,[33] M. Bellomo,[157] P. Bellos,[9] K. Belotskiy,[110] N. L. Belyaev,[110] O. Benary,[158,a] D. Benchekroun,[34a] M. Bender,[112] N. Benekos,[10] Y. Benhammou,[158] E. Benhar Noccioli,[180] J. Benitez,[75] D. P. Benjamin,[47] M. Benoit,[52] J. R. Bensinger,[26] S. Bentvelsen,[118] L. Beresford,[131] M. Beretta,[49] D. Berge,[44] E. Bergeaas Kuutmann,[169] N. Berger,[5] L. J. Bergsten,[26] J. Beringer,[18] S. Berlendis,[7] N. R. Bernard,[100] G. Bernardi,[132] C. Bernius,[150] F. U. Bernlochner,[24] T. Berry,[91] P. Berta,[97] C. Bertella,[15a] G. Bertoli,[43a,43b] I. A. Bertram,[87] G. J. Besjes,[39] O. Bessidskaia Bylund,[179] M. Bessner,[44] N. Besson,[142] A. Bethani,[98] S. Bethke,[113] A. Betti,[24] A. J. Bevan,[90] J. Beyer,[113] R. Bi,[135] R. M. B. Bianchi,[135] O. Biebel,[112] D. Biedermann,[19] R. Bielski,[35] K. Bierwagen,[97] N. V. Biesuz,[69a,69b] M. Biglietti,[72a] T. R. V. Billoud,[107] M. Bindi,[51] A. Bingul,[12d] C. Bini,[70a,70b] S. Biondi,[23b,23a] M. Birman,[177] T. Bisanz,[51] J. P. Biswal,[158] C. Bittrich,[46] D. M. Bjergaard,[47] J. E. Black,[150] K. M. Black,[25] T. Blazek,[28a] I. Bloch,[44] C. Blocker,[26] A. Blue,[55] U. Blumenschein,[90] Dr. Blunier,[144a] G. J. Bobbink,[118] V. S. Bobrovnikov,[120b,120a] S. S. Bocchetta,[94] A. Bocci,[47] D. Boerner,[179] D. Bogavac,[112] A. G. Bogdanchikov,[120b,120a] C. Bohm,[43a] V. Boisvert,[91] P. Bokan,[169,i] T. Bold,[81a] A. S. Boldyrev,[111] A. E. Bolz,[59b] M. Bomben,[132] M. Bona,[90] J. S. Bonilla,[127] M. Boonekamp,[142] A. Borisov,[140] G. Borissov,[87] J. Bortfeldt,[35] D. Bortoletto,[131] V. Bortolotto,[71a,71b] D. Boscherini,[23b] M. Bosman,[14] J. D. Bossio Sola,[30] K. Bouaouda,[34a] J. Boudreau,[135] E. V. Bouhova-Thacker,[87] D. Boumediene,[37] C. Bourdarios,[128] S. K. Boutle,[55] A. Boveia,[122] J. Boyd,[35] D. Boye,[32b] I. R. Boyko,[77] A. J. Bozson,[91] J. Bracinik,[21] N. Brahimi,[99] A. Brandt,[8] G. Brandt,[179] O. Brandt,[59a] F. Braren,[44] U. Bratzler,[161] B. Brau,[100] J. E. Brau,[127] W. D. Breaden Madden,[55] K. Brendlinger,[44] L. Brenner,[44] R. Brenner,[169] S. Bressler,[177] B. Brickwedde,[97] D. L. Briglin,[21] D. Britton,[55] D. Britzger,[113] I. Brock,[24] R. Brock,[104] G. Brooijmans,[38] T. Brooks,[91] W. K. Brooks,[144b] E. Brost,[119] J. H. Broughton,[21] P. A. Bruckman de Renstrom,[82] D. Bruncko,[28b] A. Bruni,[23b] G. Bruni,[23b] L. S. Bruni,[118] S. Bruno,[71a,71b] B. H. Brunt,[31] M. Bruschi,[23b] N. Bruscino,[135] P. Bryant,[36] L. Bryngemark,[44] T. Buanes,[17] Q. Buat,[35] P. Buchholz,[148] A. G. Buckley,[55] I. A. Budagov,[77] F. Buehrer,[50] M. K. Bugge,[130] O. Bulekov,[110] D. Bullock,[8] T. J. Burch,[119] S. Burdin,[88] C. D. Burgard,[118] A. M. Burger,[5] B. Burghgrave,[119] K. Burka,[82] S. Burke,[141] I. Burmeister,[45] J. T. P. Burr,[131] V. Büscher,[97] E. Buschmann,[51] P. Bussey,[55] J. M. Butler,[25] C. M. Buttar,[55] J. M. Butterworth,[92] P. Butti,[35] W. Buttinger,[35] A. Buzatu,[155] A. R. Buzykaev,[120b,120a] G. Cabras,[23b,23a] S. Cabrera Urbán,[171] D. Caforio,[138] H. Cai,[170] V. M. M. Cairo,[2] O. Cakir,[4a] N. Calace,[52] P. Calafiura,[18] A. Calandri,[99] G. Calderini,[132] P. Calfayan,[63] G. Callea,[40b,40a] L. P. Caloba,[78b] S. Calvente Lopez,[96] D. Calvet,[37] S. Calvet,[37] T. P. Calvet,[152] M. Calvetti,[69a,69b] R. Camacho Toro,[132] S. Camarda,[35] P. Camarri,[71a,71b] D. Cameron,[130] R. Caminal Armadans,[100] C. Camincher,[35] S. Campana,[35] M. Campanelli,[92] A. Camplani,[39] A. Campoverde,[148] V. Canale,[67a,67b] M. Cano Bret,[58c] J. Cantero,[125] T. Cao,[158] Y. Cao,[170] M. D. M. Capeans Garrido,[35] I. Caprini,[27b] M. Caprini,[27b] M. Capua,[40b,40a] R. M. Carbone,[38] R. Cardarelli,[71a] F. C. Cardillo,[146] I. Carli,[139] T. Carli,[35] G. Carlino,[67a] B. T. Carlson,[135] L. Carminati,[66a,66b] R. M. D. Carney,[43a,43b] S. Caron,[117] E. Carquin,[144b] S. Carrá,[66a,66b] G. D. Carrillo-Montoya,[35] D. Casadei,[32b] M. P. Casado,[14,j] A. F. Casha,[164] D. W. Casper,[168] R. Castelijn,[118] F. L. Castillo,[171] V. Castillo Gimenez,[171] N. F. Castro,[136a,136e] A. Catinaccio,[35] J. R. Catmore,[130] A. Cattai,[35] J. Caudron,[24] V. Cavaliere,[29] E. Cavallaro,[14] D. Cavalli,[66a] M. Cavalli-Sforza,[14] V. Cavasinni,[69a,69b] E. Celebi,[12b] F. Ceradini,[72a,72b] L. Cerda Alberich,[171] A. S. Cerqueira,[78a] A. Cerri,[153] L. Cerrito,[71a,71b] F. Cerutti,[18] A. Cervelli,[23b,23a] S. A. Cetin,[12b] A. Chafaq,[34a] D. Chakraborty,[119] S. K. Chan,[57] W. S. Chan,[118] Y. L. Chan,[61a] J. D. Chapman,[31] B. Chargeishvili,[156b] D. G. Charlton,[21] C. C. Chau,[33] C. A. Chavez Barajas,[153] S. Che,[122]

A. Chegwidden,[104] S. Chekanov,[6] S. V. Chekulaev,[165a] G. A. Chelkov,[77,k] M. A. Chelstowska,[35] C. Chen,[58a] C. H. Chen,[76] H. Chen,[29] J. Chen,[58a] J. Chen,[38] S. Chen,[133] S. J. Chen,[15c] X. Chen,[15b,l] Y. Chen,[80] Y-H. Chen,[44] H. C. Cheng,[103] H. J. Cheng,[15d] A. Cheplakov,[77] E. Cheremushkina,[140] R. Cherkaoui El Moursli,[34e] E. Cheu,[7] K. Cheung,[62] L. Chevalier,[142] V. Chiarella,[49] G. Chiarelli,[69a] G. Chiodini,[65a] A. S. Chisholm,[35,21] A. Chitan,[27b] I. Chiu,[160] Y. H. Chiu,[173] M. V. Chizhov,[77] K. Choi,[63] A. R. Chomont,[128] S. Chouridou,[159] Y. S. Chow,[118] V. Christodoulou,[92] M. C. Chu,[61a] J. Chudoba,[137] A. J. Chuinard,[101] J. J. Chwastowski,[82] L. Chytka,[126] D. Cinca,[45] V. Cindro,[89] I. A. Cioară,[24] A. Ciocio,[18] F. Cirotto,[67a,67b] Z. H. Citron,[177] M. Citterio,[66a] A. Clark,[52] M. R. Clark,[38] P. J. Clark,[48] C. Clement,[43a,43b] Y. Coadou,[99] M. Cobal,[64a,64c] A. Coccaro,[53b,53a] J. Cochran,[76] H. Cohen,[158] A. E. C. Coimbra,[177] L. Colasurdo,[117] B. Cole,[38] A. P. Colijn,[118] J. Collot,[56] P. Conde Muiño,[136a,136b] E. Coniavitis,[50] S. H. Connell,[32b] I. A. Connelly,[98] S. Constantinescu,[27b] F. Conventi,[67a,m] A. M. Cooper-Sarkar,[131] F. Cormier,[172] K. J. R. Cormier,[164] L. D. Corpe,[92] M. Corradi,[70a,70b] E. E. Corrigan,[94] F. Corriveau,[101,n] A. Cortes-Gonzalez,[35] M. J. Costa,[171] F. Costanza,[5] D. Costanzo,[146] G. Cottin,[31] G. Cowan,[91] B. E. Cox,[98] J. Crane,[98] K. Cranmer,[121] S. J. Crawley,[55] R. A. Creager,[133] G. Cree,[33] S. Crépé-Renaudin,[56] F. Crescioli,[132] M. Cristinziani,[24] V. Croft,[121] G. Crosetti,[40b,40a] A. Cueto,[96] T. Cuhadar Donszelmann,[146] A. R. Cukierman,[150] S. Czekierda,[82] P. Czodrowski,[35] M. J. Da Cunha Sargedas De Sousa,[58b,136b] C. Da Via,[98] W. Dabrowski,[81a] T. Dado,[28a,i] S. Dahbi,[34e] T. Dai,[103] F. Dallaire,[107] C. Dallapiccola,[100] M. Dam,[39] G. D'amen,[23b,23a] J. Damp,[97] J. R. Dandoy,[133] M. F. Daneri,[30] N. P. Dang,[178,f] N. D Dann,[98] M. Danninger,[172] V. Dao,[35] G. Darbo,[53b] S. Darmora,[8] O. Dartsi,[5] A. Dattagupta,[127] T. Daubney,[44] S. D'Auria,[66a,66b] W. Davey,[24] C. David,[44] T. Davidek,[139] D. R. Davis,[47] E. Dawe,[102] I. Dawson,[146] K. De,[8] R. De Asmundis,[67a] A. De Benedetti,[124] M. De Beurs,[118] S. De Castro,[23b,23a] S. De Cecco,[70a,70b] N. De Groot,[117] P. de Jong,[118] H. De la Torre,[104] F. De Lorenzi,[76] A. De Maria,[69a,69b] D. De Pedis,[70a] A. De Salvo,[70a] U. De Sanctis,[71a,71b] M. De Santis,[71a,71b] A. De Santo,[153] K. De Vasconcelos Corga,[99] J. B. De Vivie De Regie,[128] C. Debenedetti,[143] D. V. Dedovich,[77] N. Dehghanian,[3] M. Del Gaudio,[40b,40a] J. Del Peso,[96] Y. Delabat Diaz,[44] D. Delgove,[128] F. Deliot,[142] C. M. Delitzsch,[7] M. Della Pietra,[67a,67b] D. Della Volpe,[52] A. Dell'Acqua,[35] L. Dell'Asta,[25] M. Delmastro,[5] C. Delporte,[128] P. A. Delsart,[56] D. A. DeMarco,[164] S. Demers,[180] M. Demichev,[77] S. P. Denisov,[140] D. Denysiuk,[118] L. D'Eramo,[132] D. Derendarz,[82] J. E. Derkaoui,[34d] F. Derue,[132] P. Dervan,[88] K. Desch,[24] C. Deterre,[44] K. Dette,[164] M. R. Devesa,[30] P. O. Deviveiros,[35] A. Dewhurst,[141] S. Dhaliwal,[26] F. A. Di Bello,[52] A. Di Ciaccio,[71a,71b] L. Di Ciaccio,[5] W. K. Di Clemente,[133] C. Di Donato,[67a,67b] A. Di Girolamo,[35] G. Di Gregorio,[69a,69b] B. Di Micco,[72a,72b] R. Di Nardo,[100] K. F. Di Petrillo,[57] R. Di Sipio,[164] D. Di Valentino,[33] C. Diaconu,[99] M. Diamond,[164] F. A. Dias,[39] T. Dias Do Vale,[136a] M. A. Diaz,[144a] J. Dickinson,[18] E. B. Diehl,[103] J. Dietrich,[19] S. Díez Cornell,[44] A. Dimitrievska,[18] J. Dingfelder,[24] F. Dittus,[35] F. Djama,[99] T. Djobava,[156b] J. I. Djuvsland,[59a] M. A. B. Do Vale,[78c] M. Dobre,[27b] D. Dodsworth,[26] C. Doglioni,[94] J. Dolejsi,[139] Z. Dolezal,[139] M. Donadelli,[78d] J. Donini,[37] A. D'onofrio,[90] M. D'Onofrio,[88] J. Dopke,[141] A. Doria,[67a] M. T. Dova,[86] A. T. Doyle,[55] E. Drechsler,[51] E. Dreyer,[149] T. Dreyer,[51] Y. Du,[58b] F. Dubinin,[108] M. Dubovsky,[28a] A. Dubreuil,[52] E. Duchovni,[177] G. Duckeck,[112] A. Ducourthial,[132] O. A. Ducu,[107,o] D. Duda,[113] A. Dudarev,[35] A. C. Dudder,[97] E. M. Duffield,[18] L. Duflot,[128] M. Dührssen,[35] C. Dülsen,[179] M. Dumancic,[177] A. E. Dumitriu,[27b,p] A. K. Duncan,[55] M. Dunford,[59a] A. Duperrin,[99] H. Duran Yildiz,[4a] M. Düren,[54] A. Durglishvili,[156b] D. Duschinger,[46] B. Dutta,[44] D. Duvnjak,[1] M. Dyndal,[44] S. Dysch,[98] B. S. Dziedzic,[82] C. Eckardt,[44] K. M. Ecker,[113] R. C. Edgar,[103] T. Eifert,[35] G. Eigen,[17] K. Einsweiler,[18] T. Ekelof,[169] M. El Kacimi,[34c] R. El Kosseifi,[99] V. Ellajosyula,[99] M. Ellert,[169] F. Ellinghaus,[179] A. A. Elliot,[90] N. Ellis,[35] J. Elmsheuser,[29] M. Elsing,[35] D. Emeliyanov,[141] A. Emerman,[38] Y. Enari,[160] J. S. Ennis,[175] M. B. Epland,[47] J. Erdmann,[45] A. Ereditato,[20] S. Errede,[170] M. Escalier,[128] C. Escobar,[171] O. Estrada Pastor,[171] A. I. Etienvre,[142] E. Etzion,[158] H. Evans,[63] A. Ezhilov,[134] M. Ezzi,[34e] F. Fabbri,[55] L. Fabbri,[23b,23a] V. Fabiani,[117] G. Facini,[92] R. M. Faisca Rodrigues Pereira,[136a] R. M. Fakhrutdinov,[140] S. Falciano,[70a] P. J. Falke,[5] S. Falke,[5] J. Faltova,[139] Y. Fang,[15a] M. Fanti,[66a,66b] A. Farbin,[8] A. Farilla,[72a] E. M. Farina,[68a,68b] T. Farooque,[104] S. Farrell,[18] S. M. Farrington,[175] P. Farthouat,[35] F. Fassi,[34e] P. Fassnacht,[35] D. Fassouliotis,[9] M. Faucci Giannelli,[48] A. Favareto,[53b,53a] W. J. Fawcett,[31] L. Fayard,[128] O. L. Fedin,[134,q] W. Fedorko,[172] M. Feickert,[41] S. Feigl,[130] L. Feligioni,[99] C. Feng,[58b] E. J. Feng,[35] M. Feng,[47] M. J. Fenton,[55] A. B. Fenyuk,[140] L. Feremenga,[8] J. Ferrando,[44] A. Ferrari,[169] P. Ferrari,[118] R. Ferrari,[68a] D. E. Ferreira de Lima,[59b] A. Ferrer,[171] D. Ferrere,[52] C. Ferretti,[103] F. Fiedler,[97] A. Filipčič,[89] F. Filthaut,[117] K. D. Finelli,[25] M. C. N. Fiolhais,[136a,136c,r] L. Fiorini,[171] C. Fischer,[14] W. C. Fisher,[104] N. Flaschel,[44] I. Fleck,[148] P. Fleischmann,[103] R. R. M. Fletcher,[133] T. Flick,[179] B. M. Flierl,[112] L. M. Flores,[133] L. R. Flores Castillo,[61a] F. M. Follega,[73a,73b] N. Fomin,[17] G. T. Forcolin,[73a,73b] A. Formica,[142] F. A. Förster,[14] A. C. Forti,[98] A. G. Foster,[21] D. Fournier,[128] H. Fox,[87] S. Fracchia,[146] P. Francavilla,[69a,69b] M. Franchini,[23b,23a] S. Franchino,[59a] D. Francis,[35] L. Franconi,[143] M. Franklin,[57] M. Frate,[168] M. Fraternali,[68a,68b] A. N. Fray,[90] D. Freeborn,[92]

S. M. Fressard-Batraneanu,[35] B. Freund,[107] W. S. Freund,[78b] E. M. Freundlich,[45] D. C. Frizzell,[124] D. Froidevaux,[35] J. A. Frost,[131] C. Fukunaga,[161] E. Fullana Torregrosa,[171] T. Fusayasu,[114] J. Fuster,[171] O. Gabizon,[157] A. Gabrielli,[23b,23a] A. Gabrielli,[18] G. P. Gach,[81a] S. Gadatsch,[52] P. Gadow,[113] G. Gagliardi,[53b,53a] L. G. Gagnon,[107] C. Galea,[27b] B. Galhardo,[136a,136c] E. J. Gallas,[131] B. J. Gallop,[141] P. Gallus,[138] G. Galster,[39] R. Gamboa Goni,[90] K. K. Gan,[122] S. Ganguly,[177] J. Gao,[58a] Y. Gao,[88] Y. S. Gao,[150,g] C. García,[171] J. E. García Navarro,[171] J. A. García Pascual,[15a] M. Garcia-Sciveres,[18] R. W. Gardner,[36] N. Garelli,[150] V. Garonne,[130] K. Gasnikova,[44] A. Gaudiello,[53b,53a] G. Gaudio,[68a] I. L. Gavrilenko,[108] A. Gavrilyuk,[109] C. Gay,[172] G. Gaycken,[24] E. N. Gazis,[10] C. N. P. Gee,[141] J. Geisen,[51] M. Geisen,[97] M. P. Geisler,[59a] K. Gellerstedt,[43a,43b] C. Gemme,[53b] M. H. Genest,[56] C. Geng,[103] S. Gentile,[70a,70b] S. George,[91] D. Gerbaudo,[14] G. Gessner,[45] S. Ghasemi,[148] M. Ghasemi Bostanabad,[173] M. Ghneimat,[24] B. Giacobbe,[23b] S. Giagu,[70a,70b] N. Giangiacomi,[23b,23a] P. Giannetti,[69a] A. Giannini,[67a,67b] S. M. Gibson,[91] M. Gignac,[143] D. Gillberg,[33] G. Gilles,[179] D. M. Gingrich,[3,e] M. P. Giordani,[64a,64c] F. M. Giorgi,[23b] P. F. Giraud,[142] P. Giromini,[57] G. Giugliarelli,[64a,64c] D. Giugni,[66a] F. Giuli,[131] M. Giulini,[59b] S. Gkaitatzis,[159] I. Gkialas,[9,s] E. L. Gkougkousis,[14] P. Gkountoumis,[10] L. K. Gladilin,[111] C. Glasman,[96] J. Glatzer,[14] P. C. F. Glaysher,[44] A. Glazov,[44] M. Goblirsch-Kolb,[26] J. Godlewski,[82] S. Goldfarb,[102] T. Golling,[52] D. Golubkov,[140] A. Gomes,[136a,136b,136d] R. Goncalves Gama,[78a] R. Gonçalo,[136a] G. Gonella,[50] L. Gonella,[21] A. Gongadze,[77] F. Gonnella,[21] J. L. Gonski,[57] S. González de la Hoz,[171] S. Gonzalez-Sevilla,[52] L. Goossens,[35] P. A. Gorbounov,[109] H. A. Gordon,[29] B. Gorini,[35] E. Gorini,[65a,65b] A. Gorišek,[89] A. T. Goshaw,[47] C. Gössling,[45] M. I. Gostkin,[77] C. A. Gottardo,[24] C. R. Goudet,[128] D. Goujdami,[34c] A. G. Goussiou,[145] N. Govender,[32b,t] C. Goy,[5] E. Gozani,[157] I. Grabowska-Bold,[81a] P. O. J. Gradin,[169] E. C. Graham,[88] J. Gramling,[168] E. Gramstad,[130] S. Grancagnolo,[19] V. Gratchev,[134] P. M. Gravila,[27f] F. G. Gravili,[65a,65b] C. Gray,[55] H. M. Gray,[18] Z. D. Greenwood,[93,u] C. Grefe,[24] K. Gregersen,[94] I. M. Gregor,[44] P. Grenier,[150] K. Grevtsov,[44] N. A. Grieser,[124] J. Griffiths,[8] A. A. Grillo,[143] K. Grimm,[150] S. Grinstein,[14,v] Ph. Gris,[37] J.-F. Grivaz,[128] S. Groh,[97] E. Gross,[177] J. Grosse-Knetter,[51] G. C. Grossi,[93] Z. J. Grout,[92] C. Grud,[103] A. Grummer,[116] L. Guan,[103] W. Guan,[178] J. Guenther,[35] A. Guerguichon,[128] F. Guescini,[165a] D. Guest,[168] R. Gugel,[50] B. Gui,[122] T. Guillemin,[5] S. Guindon,[35] U. Gul,[55] C. Gumpert,[35] J. Guo,[58c] W. Guo,[103] Y. Guo,[58a,w] Z. Guo,[99] R. Gupta,[44] S. Gurbuz,[12c] G. Gustavino,[124] B. J. Gutelman,[157] P. Gutierrez,[124] C. Gutschow,[92] C. Guyot,[142] M. P. Guzik,[81a] C. Gwenlan,[131] C. B. Gwilliam,[88] A. Haas,[121] C. Haber,[18] H. K. Hadavand,[8] N. Haddad,[34e] A. Hadef,[58a] S. Hageböck,[24] M. Hagihara,[166] H. Hakobyan,[181,a] M. Haleem,[174] J. Haley,[125] G. Halladjian,[104] G. D. Hallewell,[99] K. Hamacher,[179] P. Hamal,[126] K. Hamano,[173] A. Hamilton,[32a] G. N. Hamity,[146] K. Han,[58a,x] L. Han,[58a] S. Han,[15d] K. Hanagaki,[79,y] M. Hance,[143] D. M. Handl,[112] B. Haney,[133] R. Hankache,[132] P. Hanke,[59a] E. Hansen,[94] J. B. Hansen,[39] J. D. Hansen,[39] M. C. Hansen,[24] P. H. Hansen,[39] K. Hara,[166] A. S. Hard,[178] T. Harenberg,[179] S. Harkusha,[105] P. F. Harrison,[175] N. M. Hartmann,[112] Y. Hasegawa,[147] A. Hasib,[48] S. Hassani,[142] S. Haug,[20] R. Hauser,[104] L. Hauswald,[46] L. B. Havener,[38] M. Havranek,[138] C. M. Hawkes,[21] R. J. Hawkings,[35] D. Hayden,[104] C. Hayes,[152] C. P. Hays,[131] J. M. Hays,[90] H. S. Hayward,[88] S. J. Haywood,[141] M. P. Heath,[48] V. Hedberg,[94] L. Heelan,[8] S. Heer,[24] K. K. Heidegger,[50] J. Heilman,[33] S. Heim,[44] T. Heim,[18] B. Heinemann,[44,z] J. J. Heinrich,[112] L. Heinrich,[121] C. Heinz,[54] J. Hejbal,[137] L. Helary,[35] A. Held,[172] S. Hellesund,[130] S. Hellman,[43a,43b] C. Helsens,[35] R. C. W. Henderson,[87] Y. Heng,[178] S. Henkelmann,[172] A. M. Henriques Correia,[35] G. H. Herbert,[19] H. Herde,[26] V. Herget,[174] Y. Hernández Jiménez,[32c] H. Herr,[97] M. G. Herrmann,[112] T. Herrmann,[46] G. Herten,[50] R. Hertenberger,[112] L. Hervas,[35] T. C. Herwig,[133] G. G. Hesketh,[92] N. P. Hessey,[165a] S. Higashino,[79] E. Higón-Rodriguez,[171] K. Hildebrand,[36] E. Hill,[173] J. C. Hill,[31] K. K. Hill,[29] K. H. Hiller,[44] S. J. Hillier,[21] M. Hils,[46] I. Hinchliffe,[18] M. Hirose,[129] D. Hirschbuehl,[179] B. Hiti,[89] O. Hladik,[137] D. R. Hlaluku,[32c] X. Hoad,[48] J. Hobbs,[152] N. Hod,[165a] M. C. Hodgkinson,[146] A. Hoecker,[35] M. R. Hoeferkamp,[116] F. Hoenig,[112] D. Hohn,[24] D. Hohov,[128] T. R. Holmes,[36] M. Holzbock,[112] M. Homann,[45] S. Honda,[166] T. Honda,[79] T. M. Hong,[135] A. Hönle,[113] B. H. Hooberman,[170] W. H. Hopkins,[127] Y. Horii,[115] P. Horn,[46] A. J. Horton,[149] L. A. Horyn,[36] J-Y. Hostachy,[56] A. Hostiuc,[145] S. Hou,[155] A. Hoummada,[34a] J. Howarth,[98] J. Hoya,[86] M. Hrabovsky,[126] I. Hristova,[19] J. Hrivnac,[128] A. Hrynevich,[106] T. Hryn'ova,[5] P. J. Hsu,[62] S.-C. Hsu,[145] Q. Hu,[29] S. Hu,[58c] Y. Huang,[15a] Z. Hubacek,[138] F. Hubaut,[99] M. Huebner,[24] F. Huegging,[24] T. B. Huffman,[131] M. Huhtinen,[35] R. F. H. Hunter,[33] P. Huo,[152] A. M. Hupe,[33] N. Huseynov,[77,d] J. Huston,[104] J. Huth,[57] R. Hyneman,[103] G. Iacobucci,[52] G. Iakovidis,[29] I. Ibragimov,[148] L. Iconomidou-Fayard,[128] Z. Idrissi,[34e] P. Iengo,[35] R. Ignazzi,[39] O. Igonkina,[118,aa] R. Iguchi,[160] T. Iizawa,[52] Y. Ikegami,[79] M. Ikeno,[79] D. Iliadis,[159] N. Ilic,[150] F. Iltzsche,[46] G. Introzzi,[68a,68b] M. Iodice,[72a] K. Iordanidou,[38] V. Ippolito,[70a,70b] M. F. Isacson,[169] N. Ishijima,[129] M. Ishino,[160] M. Ishitsuka,[162] W. Islam,[125] C. Issever,[131] S. Istin,[157] F. Ito,[166] J. M. Iturbe Ponce,[61a] R. Iuppa,[73a,73b] A. Ivina,[177] H. Iwasaki,[79] J. M. Izen,[42] V. Izzo,[67a] P. Jacka,[137] P. Jackson,[1]

R. M. Jacobs,[24] V. Jain,[2] G. Jäkel,[179] K. B. Jakobi,[97] K. Jakobs,[50] S. Jakobsen,[74] T. Jakoubek,[137] D. O. Jamin,[125] R. Jansky,[52] J. Janssen,[24] M. Janus,[51] P. A. Janus,[81a] G. Jarlskog,[94] N. Javadov,[77,d] T. Javůrek,[35] M. Javurkova,[50] F. Jeanneau,[142] L. Jeanty,[18] J. Jejelava,[156a,bb] A. Jelinskas,[175] P. Jenni,[50,cc] J. Jeong,[44] N. Jeong,[44] S. Jézéquel,[5] H. Ji,[178] J. Jia,[152] H. Jiang,[76] Y. Jiang,[58a] Z. Jiang,[150] S. Jiggins,[50] F. A. Jimenez Morales,[37] J. Jimenez Pena,[171] S. Jin,[15c] A. Jinaru,[27b] O. Jinnouchi,[162] H. Jivan,[32c] P. Johansson,[146] K. A. Johns,[7] C. A. Johnson,[63] W. J. Johnson,[145] K. Jon-And,[43a,43b] R. W. L. Jones,[87] S. D. Jones,[153] S. Jones,[7] T. J. Jones,[88] J. Jongmanns,[59a] P. M. Jorge,[136a,136b] J. Jovicevic,[165a] X. Ju,[18] J. J. Junggeburth,[113] A. Juste Rozas,[14,v] A. Kaczmarska,[82] M. Kado,[128] H. Kagan,[122] M. Kagan,[150] T. Kaji,[176] E. Kajomovitz,[157] C. W. Kalderon,[94] A. Kaluza,[97] S. Kama,[41] A. Kamenshchikov,[140] L. Kanjir,[89] Y. Kano,[160] V. A. Kantserov,[110] J. Kanzaki,[79] B. Kaplan,[121] L. S. Kaplan,[178] D. Kar,[32c] M. J. Kareem,[165b] E. Karentzos,[10] S. N. Karpov,[77] Z. M. Karpova,[77] V. Kartvelishvili,[87] A. N. Karyukhin,[140] L. Kashif,[178] R. D. Kass,[122] A. Kastanas,[43a,43b] Y. Kataoka,[160] C. Kato,[58d,58c] J. Katzy,[44] K. Kawade,[80] K. Kawagoe,[85] T. Kawamoto,[160] G. Kawamura,[51] E. F. Kay,[88] V. F. Kazanin,[120b,120a] R. Keeler,[173] R. Kehoe,[41] J. S. Keller,[33] E. Kellermann,[94] J. J. Kempster,[21] J. Kendrick,[21] O. Kepka,[137] S. Kersten,[179] B. P. Kerševan,[89] S. Ketabchi Haghighat,[164] R. A. Keyes,[101] M. Khader,[170] F. Khalil-Zada,[13] A. Khanov,[125] A. G. Kharlamov,[120b,120a] T. Kharlamova,[120b,120a] E. E. Khoda,[172] A. Khodinov,[163] T. J. Khoo,[52] E. Khramov,[77] J. Khubua,[156b] S. Kido,[80] M. Kiehn,[52] C. R. Kilby,[91] Y. K. Kim,[36] N. Kimura,[64a,64c] O. M. Kind,[19] B. T. King,[88] D. Kirchmeier,[46] J. Kirk,[141] A. E. Kiryunin,[113] T. Kishimoto,[160] D. Kisielewska,[81a] V. Kitali,[44] O. Kivernyk,[5] E. Kladiva,[28b] T. Klapdor-Kleingrothaus,[50] M. H. Klein,[103] M. Klein,[88] U. Klein,[88] K. Kleinknecht,[97] P. Klimek,[119] A. Klimentov,[29] T. Klingl,[24] T. Klioutchnikova,[35] F. F. Klitzner,[112] P. Kluit,[118] S. Kluth,[113] E. Kneringer,[74] E. B. F. G. Knoops,[99] A. Knue,[50] A. Kobayashi,[160] D. Kobayashi,[85] T. Kobayashi,[160] M. Kobel,[46] M. Kocian,[150] P. Kodys,[139] P. T. Koenig,[24] T. Koffas,[33] E. Koffeman,[118] N. M. Köhler,[113] T. Koi,[150] M. Kolb,[59b] I. Koletsou,[5] T. Kondo,[79] N. Kondrashova,[58c] K. Köneke,[50] A. C. König,[117] T. Kono,[79] R. Konoplich,[121,dd] V. Konstantinides,[92] N. Konstantinidis,[92] B. Konya,[94] R. Kopeliansky,[63] S. Koperny,[81a] K. Korcyl,[82] K. Kordas,[159] G. Koren,[158] A. Korn,[92] I. Korolkov,[14] E. V. Korolkova,[146] N. Korotkova,[111] O. Kortner,[113] S. Kortner,[113] T. Kosek,[139] V. V. Kostyukhin,[24] A. Kotwal,[47] A. Koulouris,[10] A. Kourkoumeli-Charalampidi,[68a,68b] C. Kourkoumelis,[9] E. Kourlitis,[146] V. Kouskoura,[29] A. B. Kowalewska,[82] R. Kowalewski,[173] T. Z. Kowalski,[81a] C. Kozakai,[160] W. Kozanecki,[142] A. S. Kozhin,[140] V. A. Kramarenko,[111] G. Kramberger,[89] D. Krasnopevtsev,[58a] M. W. Krasny,[132] A. Krasznahorkay,[35] D. Krauss,[113] J. A. Kremer,[81a] J. Kretzschmar,[88] P. Krieger,[164] K. Krizka,[18] K. Kroeninger,[45] H. Kroha,[113] J. Kroll,[137] J. Kroll,[133] J. Krstic,[16] U. Kruchonak,[77] H. Krüger,[24] N. Krumnack,[76] M. C. Kruse,[47] T. Kubota,[102] S. Kuday,[4b] J. T. Kuechler,[179] S. Kuehn,[35] A. Kugel,[59a] F. Kuger,[174] T. Kuhl,[44] V. Kukhtin,[77] R. Kukla,[99] Y. Kulchitsky,[105] S. Kuleshov,[144b] Y. P. Kulinich,[170] M. Kuna,[56] T. Kunigo,[83] A. Kupco,[137] T. Kupfer,[45] O. Kuprash,[158] H. Kurashige,[80] L. L. Kurchaninov,[165a] Y. A. Kurochkin,[105] A. Kurova,[110] M. G. Kurth,[15d] E. S. Kuwertz,[35] M. Kuze,[162] J. Kvita,[126] T. Kwan,[101] A. La Rosa,[113] J. L. La Rosa Navarro,[78d] L. La Rotonda,[40b,40a] F. La Ruffa,[40b,40a] C. Lacasta,[171] F. Lacava,[70a,70b] J. Lacey,[44] D. P. J. Lack,[98] H. Lacker,[19] D. Lacour,[132] E. Ladygin,[77] R. Lafaye,[5] B. Laforge,[132] T. Lagouri,[32c] S. Lai,[51] S. Lammers,[63] W. Lampl,[7] E. Lançon,[29] U. Landgraf,[50] M. P. J. Landon,[90] M. C. Lanfermann,[52] V. S. Lang,[44] J. C. Lange,[51] R. J. Langenberg,[35] A. J. Lankford,[168] F. Lanni,[29] K. Lantzsch,[24] A. Lanza,[68a] A. Lapertosa,[53b,53a] S. Laplace,[132] J. F. Laporte,[142] T. Lari,[66a] F. Lasagni Manghi,[23b,23a] M. Lassnig,[35] T. S. Lau,[61a] A. Laudrain,[128] M. Lavorgna,[67a,67b] M. Lazzaroni,[66a,66b] B. Le,[102] O. Le Dortz,[132] E. Le Guirriec,[99] E. P. Le Quilleuc,[142] M. LeBlanc,[7] T. LeCompte,[6] F. Ledroit-Guillon,[56] C. A. Lee,[29] G. R. Lee,[144a] L. Lee,[57] S. C. Lee,[155] B. Lefebvre,[101] M. Lefebvre,[173] F. Legger,[112] C. Leggett,[18] K. Lehmann,[149] N. Lehmann,[179] G. Lehmann Miotto,[35] W. A. Leight,[44] A. Leisos,[159,ee] M. A. L. Leite,[78d] R. Leitner,[139] D. Lellouch,[177] K. J. C. Leney,[92] T. Lenz,[24] B. Lenzi,[35] R. Leone,[7] S. Leone,[69a] C. Leonidopoulos,[48] G. Lerner,[153] C. Leroy,[107] R. Les,[164] A. A. J. Lesage,[142] C. G. Lester,[31] M. Levchenko,[134] J. Levêque,[5] D. Levin,[103] L. J. Levinson,[177] D. Lewis,[90] B. Li,[15b] B. Li,[103] C-Q. Li,[58a] H. Li,[58b] L. Li,[58c] M. Li,[15a] Q. Li,[15d] Q. Y. Li,[58a] S. Li,[58d,58c] X. Li,[58c] Y. Li,[148] Z. Liang,[15a] B. Liberti,[71a] A. Liblong,[164] K. Lie,[61c] S. Liem,[118] A. Limosani,[154] C. Y. Lin,[31] K. Lin,[104] T. H. Lin,[97] R. A. Linck,[63] J. H. Lindon,[21] B. E. Lindquist,[152] A. L. Lionti,[52] E. Lipeles,[133] A. Lipniacka,[17] M. Lisovyi,[59b] T. M. Liss,[170,ff] A. Lister,[172] A. M. Litke,[143] J. D. Little,[8] B. Liu,[76] B L Liu,[6] H. B. Liu,[29] H. Liu,[103] J. B. Liu,[58a] J. K. K. Liu,[131] K. Liu,[132] M. Liu,[58a] P. Liu,[18] Y. Liu,[15a] Y. L. Liu,[58a] Y. W. Liu,[58a] M. Livan,[68a,68b] A. Lleres,[56] J. Llorente Merino,[15a] S. L. Lloyd,[90] C. Y. Lo,[61b] F. Lo Sterzo,[41] E. M. Lobodzinska,[44] P. Loch,[7] A. Loesle,[50] T. Lohse,[19] K. Lohwasser,[146] M. Lokajicek,[137] J. D. Long,[170] R. E. Long,[87] L. Longo,[65a,65b] K. A. Looper,[122] J. A. Lopez,[144b] I. Lopez Paz,[98] A. Lopez Solis,[146] J. Lorenz,[112] N. Lorenzo Martinez,[5] M. Losada,[22] P. J. Lösel,[112] X. Lou,[44] X. Lou,[15a] A. Lounis,[128] J. Love,[6] P. A. Love,[87] J. J. Lozano Bahilo,[171] H. Lu,[61a] M. Lu,[58a] N. Lu,[103] Y. J. Lu,[62] H. J. Lubatti,[145]

C. Luci,[70a,70b] A. Lucotte,[56] C. Luedtke,[50] F. Luehring,[63] I. Luise,[132] L. Luminari,[70a] B. Lund-Jensen,[151] M. S. Lutz,[100] P. M. Luzi,[132] D. Lynn,[29] R. Lysak,[137] E. Lytken,[94] F. Lyu,[15a] V. Lyubushkin,[77] T. Lyubushkina,[77] H. Ma,[29] L. L. Ma,[58b] Y. Ma,[58b] G. Maccarrone,[49] A. Macchiolo,[113] C. M. Macdonald,[146] J. Machado Miguens,[133,136b] D. Madaffari,[171] R. Madar,[37] W. F. Mader,[46] A. Madsen,[44] N. Madysa,[46] J. Maeda,[80] K. Maekawa,[160] S. Maeland,[17] T. Maeno,[29] M. Maerker,[46] A. S. Maevskiy,[111] V. Magerl,[50] D. J. Mahon,[38] C. Maidantchik,[78b] T. Maier,[112] A. Maio,[136a,136b,136d] O. Majersky,[28a] S. Majewski,[127] Y. Makida,[79] N. Makovec,[128] B. Malaescu,[132] Pa. Malecki,[82] V. P. Maleev,[134] F. Malek,[56] U. Mallik,[75] D. Malon,[6] C. Malone,[31] S. Maltezos,[10] S. Malyukov,[35] J. Mamuzic,[171] G. Mancini,[49] I. Mandić,[89] J. Maneira,[136a] L. Manhaes de Andrade Filho,[78a] J. Manjarres Ramos,[46] K. H. Mankinen,[94] A. Mann,[112] A. Manousos,[74] B. Mansoulie,[142] J. D. Mansour,[15a] M. Mantoani,[51] S. Manzoni,[66a,66b] A. Marantis,[159] G. Marceca,[30] L. March,[52] L. Marchese,[131] G. Marchiori,[132] M. Marcisovsky,[137] C. A. Marin Tobon,[35] M. Marjanovic,[37] D. E. Marley,[103] F. Marroquim,[78b] Z. Marshall,[18] M. U. F. Martensson,[169] S. Marti-Garcia,[171] C. B. Martin,[122] T. A. Martin,[175] V. J. Martin,[48] B. Martin dit Latour,[17] M. Martinez,[14,v] V. I. Martinez Outschoorn,[100] S. Martin-Haugh,[141] V. S. Martoiu,[27b] A. C. Martyniuk,[92] A. Marzin,[35] L. Masetti,[97] T. Mashimo,[160] R. Mashinistov,[108] J. Masik,[98] A. L. Maslennikov,[120b,120a] L. H. Mason,[102] L. Massa,[71a,71b] P. Massarotti,[67a,67b] P. Mastrandrea,[5] A. Mastroberardino,[40b,40a] T. Masubuchi,[160] P. Mättig,[179] J. Maurer,[27b] B. Maček,[89] S. J. Maxfield,[88] D. A. Maximov,[120b,120a] R. Mazini,[155] I. Maznas,[159] S. M. Mazza,[143] G. Mc Goldrick,[164] S. P. Mc Kee,[103] A. McCarn,[103] T. G. McCarthy,[113] L. I. McClymont,[92] E. F. McDonald,[102] J. A. Mcfayden,[35] G. Mchedlidze,[51] M. A. McKay,[41] K. D. McLean,[173] S. J. McMahon,[141] P. C. McNamara,[102] C. J. McNicol,[175] R. A. McPherson,[173,n] J. E. Mdhluli,[32c] Z. A. Meadows,[100] S. Meehan,[145] T. Megy,[50] S. Mehlhase,[112] A. Mehta,[88] T. Meideck,[56] B. Meirose,[42] D. Melini,[171,gg] B. R. Mellado Garcia,[32c] J. D. Mellenthin,[51] M. Melo,[28a] F. Meloni,[44] A. Melzer,[24] S. B. Menary,[98] E. D. Mendes Gouveia,[136a] L. Meng,[88] X. T. Meng,[103] A. Mengarelli,[23b,23a] S. Menke,[113] E. Meoni,[40b,40a] S. Mergelmeyer,[19] S. A. M. Merkt,[135] C. Merlassino,[20] P. Mermod,[52] L. Merola,[67a,67b] C. Meroni,[66a] F. S. Merritt,[36] A. Messina,[70a,70b] J. Metcalfe,[6] A. S. Mete,[168] C. Meyer,[133] J. Meyer,[157] J-P. Meyer,[142] H. Meyer Zu Theenhausen,[59a] F. Miano,[153] R. P. Middleton,[141] L. Mijović,[48] G. Mikenberg,[177] M. Mikestikova,[137] M. Mikuž,[89] M. Milesi,[102] A. Milic,[164] D. A. Millar,[90] D. W. Miller,[36] A. Milov,[177] D. A. Milstead,[43a,43b] A. A. Minaenko,[140] M. Miñano Moya,[171] I. A. Minashvili,[156b] A. I. Mincer,[121] B. Mindur,[81a] M. Mineev,[77] Y. Minegishi,[160] Y. Ming,[178] L. M. Mir,[14] A. Mirto,[65a,65b] K. P. Mistry,[133] T. Mitani,[176] J. Mitrevski,[112] V. A. Mitsou,[171] M. Mittal,[58c] A. Miucci,[20] P. S. Miyagawa,[146] A. Mizukami,[79] J. U. Mjörnmark,[94] T. Mkrtchyan,[181] M. Mlynarikova,[139] T. Moa,[43a,43b] K. Mochizuki,[107] P. Mogg,[50] S. Mohapatra,[38] S. Molander,[43a,43b] R. Moles-Valls,[24] M. C. Mondragon,[104] K. Mönig,[44] J. Monk,[39] E. Monnier,[99] A. Montalbano,[149] J. Montejo Berlingen,[35] F. Monticelli,[86] S. Monzani,[66a] N. Morange,[128] D. Moreno,[22] M. Moreno Llácer,[35] P. Morettini,[53b] M. Morgenstern,[118] S. Morgenstern,[46] D. Mori,[149] M. Morii,[57] M. Morinaga,[176] V. Morisbak,[130] A. K. Morley,[35] G. Mornacchi,[35] A. P. Morris,[92] J. D. Morris,[90] L. Morvaj,[152] P. Moschovakos,[10] M. Mosidze,[156b] H. J. Moss,[146] J. Moss,[150,hh] K. Motohashi,[162] R. Mount,[150] E. Mountricha,[35] E. J. W. Moyse,[100] S. Muanza,[99] F. Mueller,[113] J. Mueller,[135] R. S. P. Mueller,[112] D. Muenstermann,[87] G. A. Mullier,[94] F. J. Munoz Sanchez,[98] P. Murin,[28b] W. J. Murray,[175,141] A. Murrone,[66a,66b] M. Muškinja,[89] C. Mwewa,[32a] A. G. Myagkov,[140,ii] J. Myers,[127] M. Myska,[138] B. P. Nachman,[18] O. Nackenhorst,[45] K. Nagai,[131] K. Nagano,[79] Y. Nagasaka,[60] M. Nagel,[50] E. Nagy,[99] A. M. Nairz,[35] Y. Nakahama,[115] K. Nakamura,[79] T. Nakamura,[160] I. Nakano,[123] H. Nanjo,[129] F. Napolitano,[59a] R. F. Naranjo Garcia,[44] R. Narayan,[11] D. I. Narrias Villar,[59a] I. Naryshkin,[134] T. Naumann,[44] G. Navarro,[22] R. Nayyar,[7] H. A. Neal,[103] P. Y. Nechaeva,[108] T. J. Neep,[142] A. Negri,[68a,68b] M. Negrini,[23b] S. Nektarijevic,[117] C. Nellist,[51] M. E. Nelson,[131] S. Nemecek,[137] P. Nemethy,[121] M. Nessi,[35,jj] M. S. Neubauer,[170] M. Neumann,[179] P. R. Newman,[21] T. Y. Ng,[61c] Y. S. Ng,[19] H. D. N. Nguyen,[99] T. Nguyen Manh,[107] E. Nibigira,[37] R. B. Nickerson,[131] R. Nicolaidou,[142] D. S. Nielsen,[39] J. Nielsen,[143] N. Nikiforou,[11] V. Nikolaenko,[140,ii] I. Nikolic-Audit,[132] K. Nikolopoulos,[21] P. Nilsson,[29] Y. Ninomiya,[79] A. Nisati,[70a] N. Nishu,[58c] R. Nisius,[113] I. Nitsche,[45] T. Nitta,[176] T. Nobe,[160] Y. Noguchi,[83] M. Nomachi,[129] I. Nomidis,[132] M. A. Nomura,[29] T. Nooney,[90] M. Nordberg,[35] N. Norjoharuddeen,[131] T. Novak,[89] O. Novgorodova,[46] R. Novotny,[138] L. Nozka,[126] K. Ntekas,[168] E. Nurse,[92] F. Nuti,[102] F. G. Oakham,[33,e] H. Oberlack,[113] J. Ocariz,[132] A. Ochi,[80] I. Ochoa,[38] J. P. Ochoa-Ricoux,[144a] K. O'Connor,[26] S. Oda,[85] S. Odaka,[79] S. Oerdek,[51] A. Oh,[98] S. H. Oh,[47] C. C. Ohm,[151] H. Oide,[53b,53a] M. L. Ojeda,[164] H. Okawa,[166] Y. Okazaki,[83] Y. Okumura,[160] T. Okuyama,[79] A. Olariu,[27b] L. F. Oleiro Seabra,[136a] S. A. Olivares Pino,[144a] D. Oliveira Damazio,[29] J. L. Oliver,[1] M. J. R. Olsson,[36] A. Olszewski,[82] J. Olszowska,[82] D. C. O'Neil,[149] A. Onofre,[136a,136e] K. Onogi,[115] P. U. E. Onyisi,[11] H. Oppen,[130] M. J. Oreglia,[36] G. E. Orellana,[86] Y. Oren,[158] D. Orestano,[72a,72b] E. C. Orgill,[98] N. Orlando,[61b] A. A. O'Rourke,[44] R. S. Orr,[164]

B. Osculati,[53b,53a,a] V. O'Shea,[55] R. Ospanov,[58a] G. Otero y Garzon,[30] H. Otono,[85] M. Ouchrif,[34d] F. Ould-Saada,[130] A. Ouraou,[142] Q. Ouyang,[15a] M. Owen,[55] R. E. Owen,[21] V. E. Ozcan,[12c] N. Ozturk,[8] J. Pacalt,[126] H. A. Pacey,[31] K. Pachal,[149] A. Pacheco Pages,[14] L. Pacheco Rodriguez,[142] C. Padilla Aranda,[14] S. Pagan Griso,[18] M. Paganini,[180] G. Palacino,[63] S. Palazzo,[40b,40a] S. Palestini,[35] M. Palka,[81b] D. Pallin,[37] I. Panagoulias,[10] C. E. Pandini,[35] J. G. Panduro Vazquez,[91] P. Pani,[35] G. Panizzo,[64a,64c] L. Paolozzi,[52] T. D. Papadopoulou,[10] K. Papageorgiou,[9,s] A. Paramonov,[6] D. Paredes Hernandez,[61b] S. R. Paredes Saenz,[131] B. Parida,[163] A. J. Parker,[87] K. A. Parker,[44] M. A. Parker,[31] F. Parodi,[53b,53a] J. A. Parsons,[38] U. Parzefall,[50] V. R. Pascuzzi,[164] J. M. P. Pasner,[143] E. Pasqualucci,[70a] S. Passaggio,[53b] F. Pastore,[91] P. Pasuwan,[43a,43b] S. Pataraia,[97] J. R. Pater,[98] A. Pathak,[178,f] T. Pauly,[35] B. Pearson,[113] M. Pedersen,[130] L. Pedraza Diaz,[117] R. Pedro,[136a,136b] S. V. Peleganchuk,[120b,120a] O. Penc,[137] C. Peng,[15d] H. Peng,[58a] B. S. Peralva,[78a] M. M. Perego,[128] A. P. Pereira Peixoto,[136a] D. V. Perepelitsa,[29] F. Peri,[19] L. Perini,[66a,66b] H. Pernegger,[35] S. Perrella,[67a,67b] V. D. Peshekhonov,[77,a] K. Peters,[44] R. F. Y. Peters,[98] B. A. Petersen,[35] T. C. Petersen,[39] E. Petit,[56] A. Petridis,[1] C. Petridou,[159] P. Petroff,[128] M. Petrov,[131] F. Petrucci,[72a,72b] M. Pettee,[180] N. E. Pettersson,[100] A. Peyaud,[142] R. Pezoa,[144b] T. Pham,[102] F. H. Phillips,[104] P. W. Phillips,[141] M. W. Phipps,[170] G. Piacquadio,[152] E. Pianori,[18] A. Picazio,[100] M. A. Pickering,[131] R. H. Pickles,[98] R. Piegaia,[30] J. E. Pilcher,[36] A. D. Pilkington,[98] M. Pinamonti,[71a,71b] J. L. Pinfold,[3] M. Pitt,[177] L. Pizzimento,[71a,71b] M-A. Pleier,[29] V. Pleskot,[139] E. Plotnikova,[77] D. Pluth,[76] P. Podberezko,[120b,120a] R. Poettgen,[94] R. Poggi,[52] L. Poggioli,[128] I. Pogrebnyak,[104] D. Pohl,[24] I. Pokharel,[51] G. Polesello,[68a] A. Poley,[18] A. Policicchio,[70a,70b] R. Polifka,[35] A. Polini,[23b] C. S. Pollard,[44] V. Polychronakos,[29] D. Ponomarenko,[110] L. Pontecorvo,[70a] G. A. Popeneciu,[27d] D. M. Portillo Quintero,[132] S. Pospisil,[138] K. Potamianos,[44] I. N. Potrap,[77] C. J. Potter,[31] H. Potti,[11] T. Poulsen,[94] J. Poveda,[35] T. D. Powell,[146] M. E. Pozo Astigarraga,[35] P. Pralavorio,[99] S. Prell,[76] D. Price,[98] M. Primavera,[65a] S. Prince,[101] N. Proklova,[110] K. Prokofiev,[61c] F. Prokoshin,[144b] S. Protopopescu,[29] J. Proudfoot,[6] M. Przybycien,[81a] A. Puri,[170] P. Puzo,[128] J. Qian,[103] Y. Qin,[98] A. Quadt,[51] M. Queitsch-Maitland,[44] A. Qureshi,[1] P. Rados,[102] F. Ragusa,[66a,66b] G. Rahal,[95] J. A. Raine,[52] S. Rajagopalan,[29] A. Ramirez Morales,[90] T. Rashid,[128] S. Raspopov,[5] M. G. Ratti,[66a,66b] D. M. Rauch,[44] F. Rauscher,[112] S. Rave,[97] B. Ravina,[146] I. Ravinovich,[177] J. H. Rawling,[98] M. Raymond,[35] A. L. Read,[130] N. P. Readioff,[56] M. Reale,[65a,65b] D. M. Rebuzzi,[68a,68b] A. Redelbach,[174] G. Redlinger,[29] R. Reece,[143] R. G. Reed,[32c] K. Reeves,[42] L. Rehnisch,[19] J. Reichert,[133] D. Reikher,[158] A. Reiss,[97] C. Rembser,[35] H. Ren,[15d] M. Rescigno,[70a] S. Resconi,[66a] E. D. Resseguie,[133] S. Rettie,[172] E. Reynolds,[21] O. L. Rezanova,[120b,120a] P. Reznicek,[139] E. Ricci,[73a,73b] R. Richter,[113] S. Richter,[44] E. Richter-Was,[81b] O. Ricken,[24] M. Ridel,[132] P. Rieck,[113] C. J. Riegel,[179] O. Rifki,[44] M. Rijssenbeek,[152] A. Rimoldi,[68a,68b] M. Rimoldi,[20] L. Rinaldi,[23b] G. Ripellino,[151] B. Ristić,[87] E. Ritsch,[35] I. Riu,[14] J. C. Rivera Vergara,[144a] F. Rizatdinova,[125] E. Rizvi,[90] C. Rizzi,[14] R. T. Roberts,[98] S. H. Robertson,[101,n] D. Robinson,[31] J. E. M. Robinson,[44] A. Robson,[55] E. Rocco,[97] C. Roda,[69a,69b] Y. Rodina,[99] S. Rodriguez Bosca,[171] A. Rodriguez Perez,[14] D. Rodriguez Rodriguez,[171] A. M. Rodríguez Vera,[165b] S. Roe,[35] C. S. Rogan,[57] O. Røhne,[130] R. Röhrig,[113] C. P. A. Roland,[63] J. Roloff,[57] A. Romaniouk,[110] M. Romano,[23b,23a] N. Rompotis,[88] M. Ronzani,[121] L. Roos,[132] S. Rosati,[70a] K. Rosbach,[50] N-A. Rosien,[51] B. J. Rosser,[133] E. Rossi,[44] E. Rossi,[72a,72b] E. Rossi,[67a,67b] L. P. Rossi,[53b] L. Rossini,[66a,66b] J. H. N. Rosten,[31] R. Rosten,[14] M. Rotaru,[27b] J. Rothberg,[145] D. Rousseau,[128] D. Roy,[32c] A. Rozanov,[99] Y. Rozen,[157] X. Ruan,[32c] F. Rubbo,[150] F. Rühr,[50] A. Ruiz-Martinez,[171] Z. Rurikova,[50] N. A. Rusakovich,[77] H. L. Russell,[101] J. P. Rutherfoord,[7] E. M. Rüttinger,[44,kk] Y. F. Ryabov,[134] M. Rybar,[170] G. Rybkin,[128] S. Ryu,[6] A. Ryzhov,[140] G. F. Rzehorz,[51] P. Sabatini,[51] G. Sabato,[118] S. Sacerdoti,[128] H. F-W. Sadrozinski,[143] R. Sadykov,[77] F. Safai Tehrani,[70a] P. Saha,[119] M. Sahinsoy,[59a] A. Sahu,[179] M. Saimpert,[44] M. Saito,[160] T. Saito,[160] H. Sakamoto,[160] A. Sakharov,[121,dd] D. Salamani,[52] G. Salamanna,[72a,72b] J. E. Salazar Loyola,[144b] P. H. Sales De Bruin,[169] D. Salihagic,[113] A. Salnikov,[150] J. Salt,[171] D. Salvatore,[40b,40a] F. Salvatore,[153] A. Salvucci,[61a,61b,61c] A. Salzburger,[35] J. Samarati,[35] D. Sammel,[50] D. Sampsonidis,[159] D. Sampsonidou,[159] J. Sánchez,[171] A. Sanchez Pineda,[64a,64c] H. Sandaker,[130] C. O. Sander,[44] M. Sandhoff,[179] C. Sandoval,[22] D. P. C. Sankey,[141] M. Sannino,[53b,53a] Y. Sano,[115] A. Sansoni,[49] C. Santoni,[37] H. Santos,[136a] I. Santoyo Castillo,[153] A. Santra,[171] A. Sapronov,[77] J. G. Saraiva,[136a,136d] O. Sasaki,[79] K. Sato,[166] E. Sauvan,[5] P. Savard,[164,e] N. Savic,[113] R. Sawada,[160] C. Sawyer,[141] L. Sawyer,[93,u] C. Sbarra,[23b] A. Sbrizzi,[23b,23a] T. Scanlon,[92] J. Schaarschmidt,[145] P. Schacht,[113] B. M. Schachtner,[112] D. Schaefer,[36] L. Schaefer,[133] J. Schaeffer,[97] S. Schaepe,[35] U. Schäfer,[97] A. C. Schaffer,[128] D. Schaile,[112] R. D. Schamberger,[152] N. Scharmberg,[98] V. A. Schegelsky,[134] D. Scheirich,[139] F. Schenck,[19] M. Schernau,[168] C. Schiavi,[53b,53a] S. Schier,[143] L. K. Schildgen,[24] Z. M. Schillaci,[26] E. J. Schioppa,[35] M. Schioppa,[40b,40a] K. E. Schleicher,[50] S. Schlenker,[35] K. R. Schmidt-Sommerfeld,[113] K. Schmieden,[35] C. Schmitt,[97] S. Schmitt,[44] S. Schmitz,[97] J. C. Schmoeckel,[44] U. Schnoor,[50] L. Schoeffel,[142] A. Schoening,[59b] E. Schopf,[131] M. Schott,[97] J. F. P. Schouwenberg,[117]

J. Schovancova,[35] S. Schramm,[52] A. Schulte,[97] H-C. Schultz-Coulon,[59a] M. Schumacher,[50] B. A. Schumm,[143] Ph. Schune,[142] A. Schwartzman,[150] T. A. Schwarz,[103] Ph. Schwemling,[142] R. Schwienhorst,[104] A. Sciandra,[24] G. Sciolla,[26] M. Scornajenghi,[40b,40a] F. Scuri,[69a] F. Scutti,[102] L. M. Scyboz,[113] C. D. Sebastiani,[70a,70b] P. Seema,[19] S. C. Seidel,[116] A. Seiden,[143] T. Seiss,[36] J. M. Seixas,[78b] G. Sekhniaidze,[67a] K. Sekhon,[103] S. J. Sekula,[41] N. Semprini-Cesari,[23b,23a] S. Sen,[47] S. Senkin,[37] C. Serfon,[130] L. Serin,[128] L. Serkin,[64a,64b] M. Sessa,[58a] H. Severini,[124] F. Sforza,[167] A. Sfyrla,[52] E. Shabalina,[51] J. D. Shahinian,[143] N. W. Shaikh,[43a,43b] L. Y. Shan,[15a] R. Shang,[170] J. T. Shank,[25] M. Shapiro,[18] A. S. Sharma,[1] A. Sharma,[131] P. B. Shatalov,[109] K. Shaw,[153] S. M. Shaw,[98] A. Shcherbakova,[134] Y. Shen,[124] N. Sherafati,[33] A. D. Sherman,[25] P. Sherwood,[92] L. Shi,[155,ll] S. Shimizu,[79] C. O. Shimmin,[180] M. Shimojima,[114] I. P. J. Shipsey,[131] S. Shirabe,[85] M. Shiyakova,[77] J. Shlomi,[177] A. Shmeleva,[108] D. Shoaleh Saadi,[107] M. J. Shochet,[36] S. Shojaii,[102] D. R. Shope,[124] S. Shrestha,[122] E. Shulga,[110] P. Sicho,[137] A. M. Sickles,[170] P. E. Sidebo,[151] E. Sideras Haddad,[32c] O. Sidiropoulou,[35] A. Sidoti,[23b,23a] F. Siegert,[46] Dj. Sijacki,[16] J. Silva,[136a] M. Silva Jr.,[178] M. V. Silva Oliveira,[78a] S. B. Silverstein,[43a] S. Simion,[128] E. Simioni,[97] M. Simon,[97] R. Simoniello,[97] P. Sinervo,[164] N. B. Sinev,[127] M. Sioli,[23b,23a] G. Siragusa,[174] I. Siral,[103] S. Yu. Sivoklokov,[111] J. Sjölin,[43a,43b] P. Skubic,[124] M. Slater,[21] T. Slavicek,[138] M. Slawinska,[82] K. Sliwa,[167] R. Slovak,[139] V. Smakhtin,[177] B. H. Smart,[5] J. Smiesko,[28a] N. Smirnov,[110] S. Yu. Smirnov,[110] Y. Smirnov,[110] L. N. Smirnova,[111] O. Smirnova,[94] J. W. Smith,[51] M. Smizanska,[87] K. Smolek,[138] A. Smykiewicz,[82] A. A. Snesarev,[108] I. M. Snyder,[127] S. Snyder,[29] R. Sobie,[173,n] A. M. Soffa,[168] A. Soffer,[158] A. Søgaard,[48] D. A. Soh,[155] G. Sokhrannyi,[89] C. A. Solans Sanchez,[35] M. Solar,[138] E. Yu. Soldatov,[110] U. Soldevila,[171] A. A. Solodkov,[140] A. Soloshenko,[77] O. V. Solovyanov,[140] V. Solovyev,[134] P. Sommer,[146] H. Son,[167] W. Song,[141] W. Y. Song,[165b] A. Sopczak,[138] F. Sopkova,[28b] C. L. Sotiropoulou,[69a,69b] S. Sottocornola,[68a,68b] R. Soualah,[64a,64c,mm] A. M. Soukharev,[120b,120a] D. South,[44] B. C. Sowden,[91] S. Spagnolo,[65a,65b] M. Spalla,[113] M. Spangenberg,[175] F. Spanò,[91] D. Sperlich,[19] T. M. Spieker,[59a] R. Spighi,[23b] G. Spigo,[35] L. A. Spiller,[102] D. P. Spiteri,[55] M. Spousta,[139] A. Stabile,[66a,66b] R. Stamen,[59a] S. Stamm,[19] E. Stanecka,[82] R. W. Stanek,[6] C. Stanescu,[72a] B. Stanislaus,[131] M. M. Stanitzki,[44] B. Stapf,[118] S. Stapnes,[130] E. A. Starchenko,[140] G. H. Stark,[36] J. Stark,[56] S. H Stark,[39] P. 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